Local deformation monitoring using GPS in an open pit mine: initial study

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Abstract High-performance GPS RTK software has been developed within the Geodetic Research Laboratory (GRL) at the University of New Brunswick (UNB). This software was initially designed for gantry crane auto-steering. Due to limitations with classical geodetic deformation monitoring techniques, the Canadian Centre for Geodetic Engineering (CCGE) at UNB has decided to augment its fully automated deformation monitoring system with GPS. As a result, the GRL and CCGE have combined efforts to achieve the required precision. As a first step, tests of the GPS real-time kinematic (RTK) software have been carried out at Highland Valley Copper Mine in British Columbia, Canada. An open-pit mine environment places certain constraints on the achievable accuracies attainable with GPS. Consequently, the software has been modified to meet the needs of this particular project and data have been post-processed for analysis. This paper describes the approach taken at UNB to address high precision requirements in a constrained signal availability environment. Technical and scientific aspects of the UNB software, especially in handling two predominant errors (residual tropospheric zenith delay and multipath) at the mine, are discussed. Results of tests that have been carried out at the mine are presented.

Introduction

The University of New Brunswick (UNB) real-time kinematic (RTK) software, initially designed for a gantry crane auto-steering system, is able to provide navigation solutions in real time at a 10-Hz update rate, commensurate with the dual-frequency data rate. The software for this system works in conjunction with a GPS receiver and IEEE 108.11b-compatible 2.4-GHz wireless LAN (WLAN) master unit at a base station, and two dual-frequency GPS receivers with WLAN adaptors installed on the cranes (Kim et al. 2002, 2003).

Recently, tests of this software for deformation monitoring have been carried out at the Highland Valley Copper Mine in British Columbia, Canada. For the purpose of this case study, float ambiguity estimation routines based on sequential least-squares estimation and batch processing routines have been implemented. In the original UNB RTK software, an epoch-by-epoch solution approach is used. The main reason for this modification was poor satellite visibility within the confines of the mine. In this initial assessment, real-time operation was not attempted. Data collected by the GPS receivers were post-processed.

Local deformation monitoring in an open pit mine

When monitoring deformations by means of precision surveys, several reference stations are typically set up, against which the displacements of object points are calculated. To ensure that sound conclusions are made based upon analysis of the displacements, it is necessary to ensure that the reference stations are, in fact, stable. Otherwise incorrect conclusions may be drawn. To obtain the displacements of the object points, the stability of the reference points must be confirmed and any unstable points identified. Deformation monitoring in an open pit mine poses some interesting challenges. In this setting, height differences are extreme. As an example, 650-m elevation changes over 2.0-km baselines can occur. Recently, the Canadian Centre for Geodetic Engineering (CCGE) at UNB developed a fully automated system for monitoring steep embankments (Duffy et al. 2001; Wilkins et al. 2003) and slope stability. The system utilizes robotic total stations (RTS) and a number of retroreflecting prisms mounted on the monitored object. In order to reduce pointing errors and, in particular, the effects of atmospheric refraction to the millimeter level, the distances to the target prisms must be within a few

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hundred meters. This means that in large open pit mines the robotic total stations must be placed at the bottom of the pit, and as near as possible to the monitored slope. This poses the problem of having RTSs located in an unstable environment with a limited visibility to the stable reference targets located outside the rim of the pit. The current work at CCGE concentrates on combining RTSs with GPS into a hybrid monitoring system in which GPS would control the stability of the RTS. To make such a hybrid system useful for high precision and fully automated monitoring of deformations, two requirements must be fulfilled: (1) accuracy of controlling the stability of the RTSs must be within a few millimeters at the 95% confidence level (particularly in height changes), and (2) RTS position corrections must be derived from GPS data in a fully automated mode.

The purpose of this investigation is to address the first problem, i.e. how to achieve millimeter accuracy in GPS determination of displacements.

Biases and errors of interest

The quality of GPS positioning is dependent on a number of factors. To attain high-precision positioning results, we need to identify the error sources that impact the quality of the measurements. Some of the error sources have systematic characteristics while others have quasi-random characteristics. For example, the effects of cycle slips and receiver clock jumps can be easily captured in either the measurement or the parameter domain due to their systematic characteristics. Their systematic effects on the carrier phase measurements can be almost completely removed once they are correctly identified. On the other hand, multipath, diffraction, ionospheric scintillation, etc. have temporal and spatial characteristics which are more or less quasi-random. These quasi-random errors cannot be completely eliminated. Instead, they must be handled using a rigorous mathematical approach to isolate their effects as much as possible from parameter estimates.

In terms of data processing, therefore, it is important to know whether we can remove error effects by means of suitable procedures such as the single-difference (SD) or double-difference (DD) process. If we know that some errors cannot be removed completely, it is also important to know whether the residual effects of these errors can be considered negligible. Otherwise, we may fail to attain high-precision positioning results because the error sources can deteriorate the quality of the measurements and, subsequently, the quality of positioning results. In high-precision positioning for local deformation monitoring at an open pit mine, for example, we are interested in assessing the following errors: (1) residual tropospheric delay and (2) multipath.

Residual tropospheric delay

When processing GPS data, a value for the tropospheric delay is typically predicted using empirical models which, in general, must be provided with measured or standard values of ambient temperature, pressure and relative humidity. Unfortunately, even with accurate values, these models rarely predict the true delay with a high degree of accuracy. The residual tropospheric delay is the remaining part of the tropospheric delay not predicted by empirical models. It can be the largest remaining error source in dual-frequency precision positioning (Collins and Langley 1997). Like many other spatially dependent error sources, the effects of the tropospheric delay are usually negligible in relative positioning in short-baseline environments. If there are large height differences between the base and rover antennas, differential tropospheric delays may be significant, depending on meteorological conditions in the vicinity of the base and rover stations. If significant differences in meteorological conditions exist between stations, tropospheric delays cannot be assumed to have been completely cancelled by the double-differencing process.

Multipath

From the simplest approach of selecting an optimal antenna location, to the most complicated receiver technology, a number of multipath mitigation techniques have been proposed to account for the effects of multipath in GPS code and carrier phase measurements. Although recent receiver technologies have significantly improved medium and long delay multipath performance, multipath mitigation techniques for short delays (due to close-by reflectors) are not as effective (Braasch and Van Dierendonck 1999; Weill 2003). Multipath experienced at two or more independent antennas is spatially correlated within a small area because each antenna is exposed to the same multipath environment. Except for this case, multipath is not usually spatially correlated. Therefore, the effects of multipath can be significant in relative positioning (even on short-baselines) and cannot be cancelled by double-differencing. Multipath due to specular reflection on a smooth surface shows an apparent daily correlation due to repeated satellite-receiver-reflecting object geometry. However, multipath due to diffraction (reflection from the edges or corners of the reflecting objects) and diffusion (reflection from rough surfaces) does not usually show such an apparent day-by-day correlation. Typically, in open-pit mine environments, multipath due to diffraction and diffusion occurs more often than specular reflection. Therefore, we cannot take advantage of the multipath patterns repeated daily at stationary stations.

UNB approach

The challenge in attaining sub-centimeter accuracy positioning at the open-pit mine comes from mainly the residual (unmodeled) tropospheric delay due to extreme height differences between two GPS monitoring stations. Another challenge is short delay multipath, especially that due to diffraction and diffusion whose patterns do not repeat daily. It cannot be easily removed by data "stacking" or other means.

UNB3 tropospheric delay model

The original definition of the UNB3 composite model is based on the zenith delay algorithms of Saastamoinen (1973), the mapping functions of Niell (1996) and a table of surface atmospheric values derived from the US 1966 Standard Atmosphere Supplements. The kernel of the UNB3 model is a look-up table of five values of atmospheric parameters that vary with respect to latitude and day-of-year. Linear interpolation is applied between latitudes, and a sinusoidal function of the day-of-year attempts to model the seasonal variation. The parameters are total pressure, temperature and water vapor pressure at mean sea-level, and two lapse rate parameters for temperature and water vapor. The lapse rates are used to scale the pressures and temperature to the user's altitude. The typical formulation of the tropospheric delay is:

$$
\begin{aligned}
T_i^k &= t_i^z \cdot m_i^k \\
t_i^z &= t_i^z(hyd) + t_i^z(wet) \\
m_i^k &= \frac{t_i^z(hyd) \cdot m_i^k(hyd) + t_i^z(wet) \cdot m_i^k(wet)}{t_i^z(hyd) + t_i^z(wet)},
\end{aligned}
\tag{1}
$$

where at the antenna of receiver i, the delay on the signal from satellite k is a function of the delays in the zenith direction caused by the atmospheric gases in hydrostatic equilibrium and by those gases not in hydrostatic equilibrium (primarily water vapor), $t_i^z(hyd)$ and $t_i^z(wet)$ respectively; and their mapping functions, $m_i^k(hyd)$ and $m_i^k(wet)$ respectively. The mapping functions are usually described as functions of the satellite elevation angle. By introducing a residual zenith delay parameter r_i^z in the formulation and assuming no errors in the mapping function, we have

$$
T_i^k = \left(t_i^z + r_i^z\right) \cdot m_i^k \tag{2}
$$

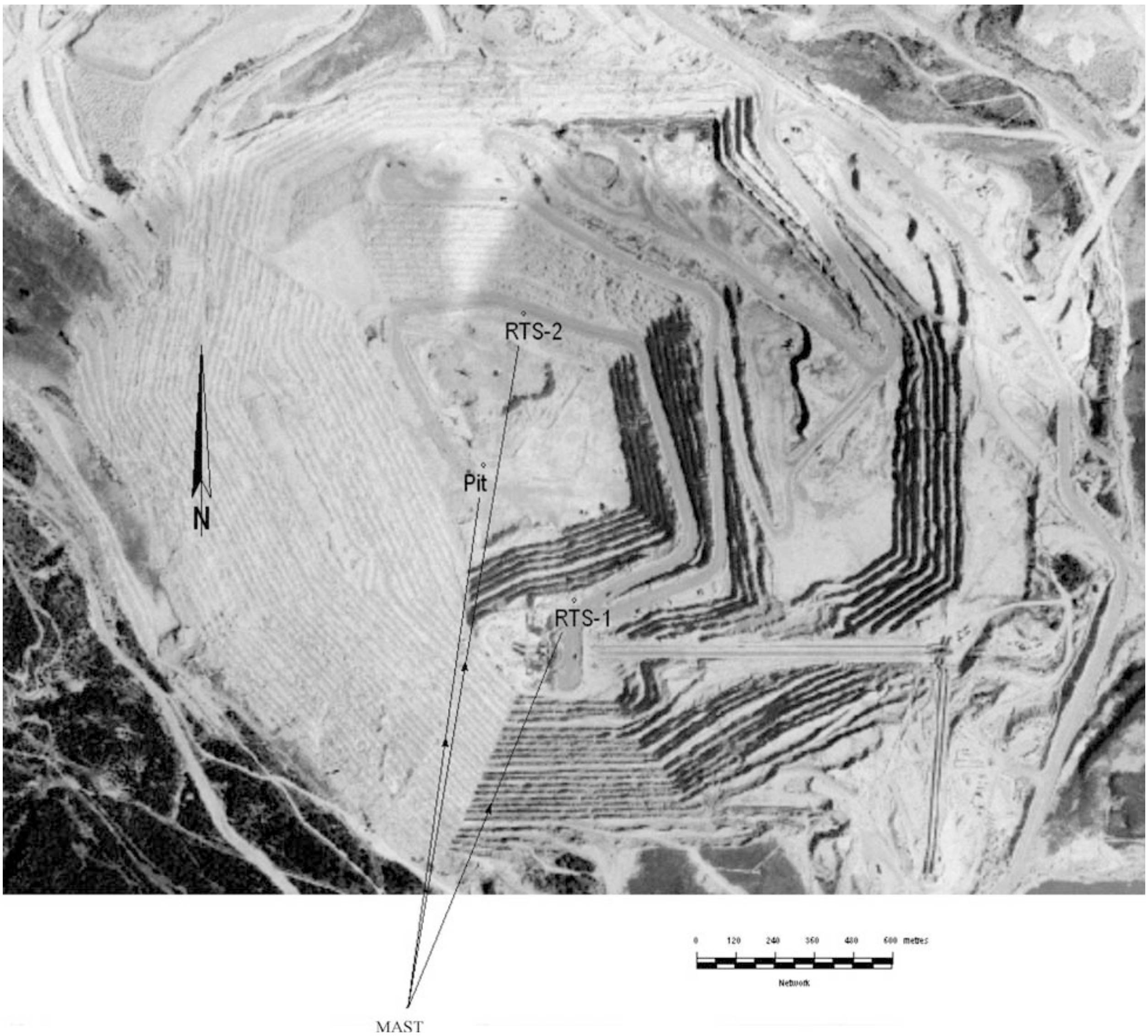

Fig. 1
GPS reference and monitoring stations located outside and inside of an open-pit mine

Table 1
Approximate distances and heights between reference and monitoring stations

Monitoring stations	Slant distance (km)	Height difference (km)
RTS1-MAST	1.4	−0.5
RTS2-MAST	2.2	−0.4
PIT-MAST	1.8	−0.6

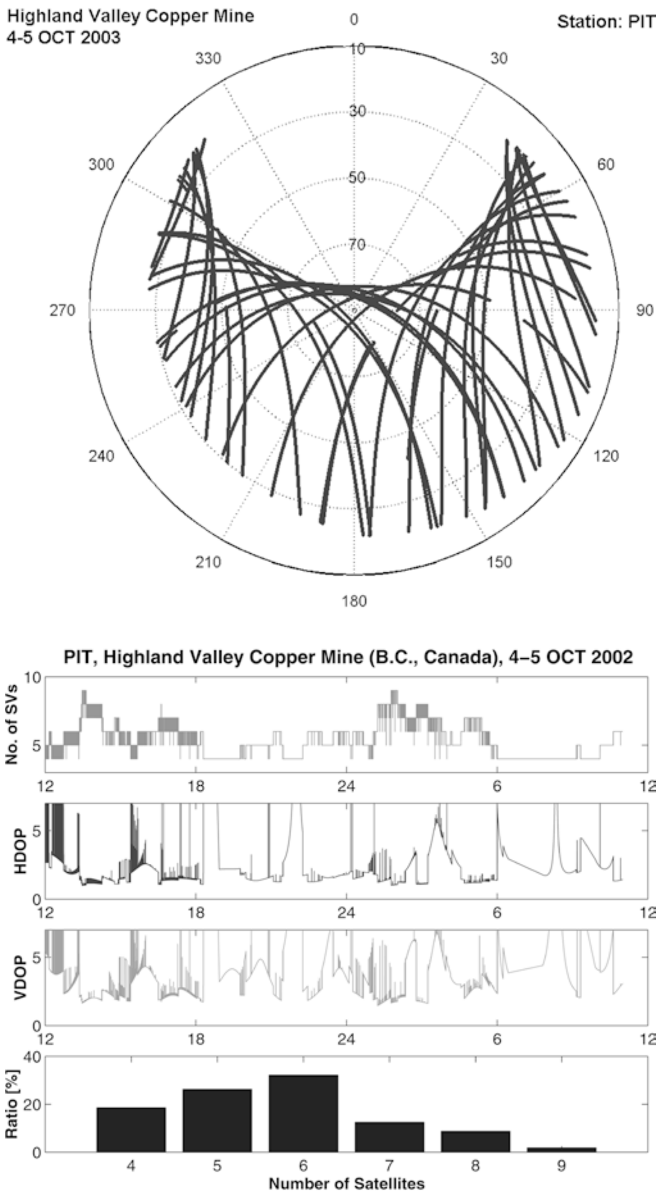

Fig. 2
Skyplot over 24 h at PIT (*above*) and number of satellites and (horizontal and vertical) DOP values (*panels below*). Elevation cut-off angle due to the open-pit environment ranges from 15 to 35 degrees

The differential tropospheric delay between satellites k and l and stations i and j is given by:

$$T_{ij}^{kl} = \left(T_j^l - T_j^k\right) - \left(T_i^l - T_i^k\right)$$
$$= \left(t_j^z + r_j^z\right)\left(m_j^l - m_j^k\right) - \left(t_i^z + r_i^z\right)\left(m_i^l - m_i^k\right). \qquad (3)$$

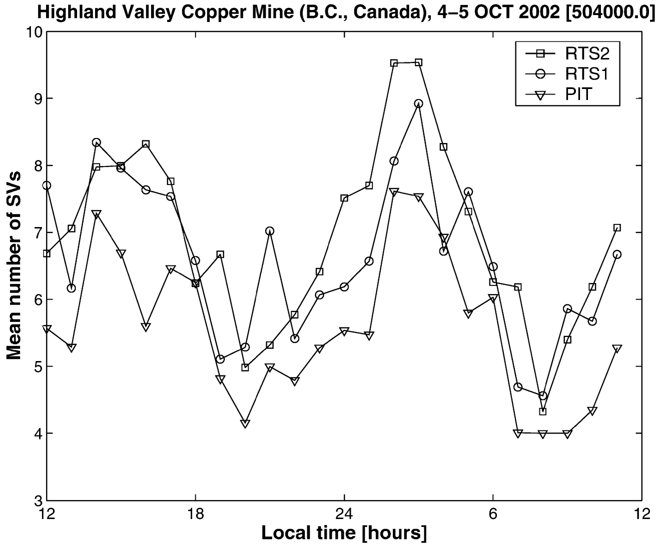

Fig. 3
Mean number of visible satellites for individual 1-h session over 24 h

Fixing the tropospheric delay at the reference station and estimating the relative delay r_j^z at the secondary station gives, with partial derivatives:

$$\frac{\partial T_{ij}^{kl}}{\partial r_j^z} = m_j^l - m_j^k \qquad (4)$$

Multipath mitigation

The main approach employed to mitigate multipath is using an optimal inter-frequency carrier phase linear combination of the L1 and L2 observations (Kim and Langley 2001; Kim and Langley 2003). A generic inter-frequency carrier phase linear combination of the L1 and L2 observations is:

$$k_1\Phi_1 + k_2\Phi_2 = (k_1 + k_2)\rho + k_1\lambda_1 N_1 + k_2\lambda_2 N_2 + k_1 b_1 + k_2 b_2 + k_1\varepsilon_1 + k_2\varepsilon_2 \qquad (5)$$

where Φ is the measured carrier phase (m); ρ is the geometric range from antenna phase center to GPS satellite; λ is the carrier wavelength (m/cycle); N is integer ambiguity (cycle); b includes biases and errors such as multipath, diffraction, ionospheric scintillation, etc.; ϵ is measurement noise; and subscripts "1" and "2" represent L1 and L2 frequencies respectively. Since we can divide the term k_1+k_2 combined with on both sides, an equivalent mathematical expression is:

$$k_1 + k_2 = 1 \qquad (6)$$

Obtaining an optimal inter-frequency carrier phase linear combination of the L1 and L2 observations is equivalent to solving $\mathbf{K_1}$ and $\mathbf{K_2}$ in the following matrix equation:

$$\min_{\mathbf{K_1},\,\mathbf{K_2}} \left(\mathbf{KQK^T}\right), \quad \text{with } \mathbf{K_1} + \mathbf{K_2} = \mathbf{I}, \qquad (7)$$

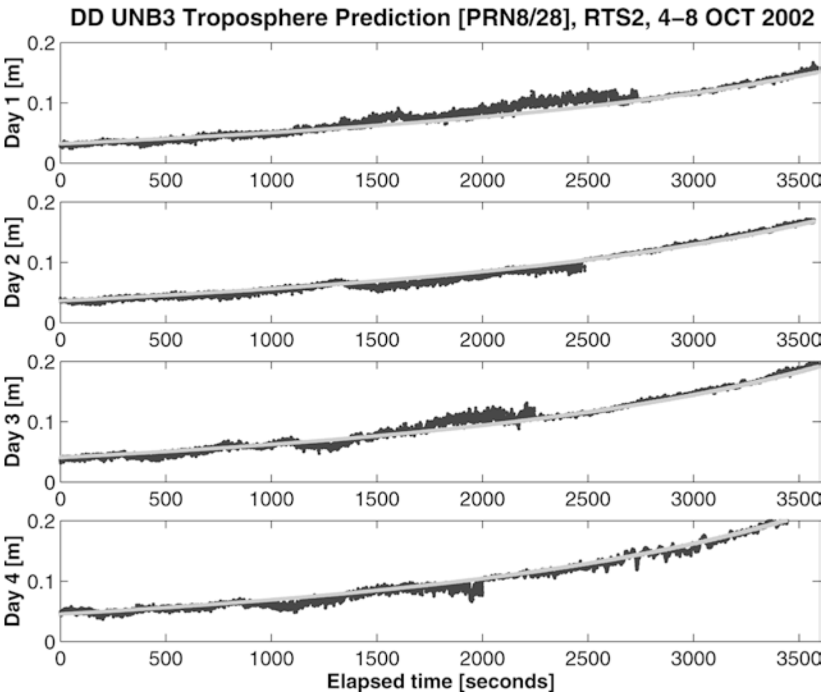

Fig. 4
Comparison of the DD tropospheric delay "observable" and UNB3 prediction values for the same 1-h session over four consecutive days. Satellite pair PRN8/28 and stations MAST and RTS2 are used

where

$$\begin{aligned} \mathbf{K} &= [\,\mathbf{K}_1 \quad \mathbf{K}_2\,] \\ \mathbf{Q} &= \begin{bmatrix} \mathbf{Q}_1 & \mathbf{Q}_{1,2} \\ \mathbf{Q}_{2,1} & \mathbf{Q}_2 \end{bmatrix} \end{aligned} \tag{8}$$

and **Q** is the variance-covariance matrix and **I** is an identity matrix. Unfortunately, an analytical solution for Eq. (7) is not available because the number of unknown parameters is much larger than the number of measurements. For example, if the number of measurements is n, the number of unknown parameters becomes $2n^2$. Alternatively, we can find $\mathbf{K}_1$ and $\mathbf{K}_2$ which guarantee an upper bound:

$$\mathbf{KQK}^{\mathrm{T}} \leqslant \frac{1}{2}(\mathbf{Q}_{\mathrm{L1}} + \mathbf{Q}_{\mathrm{L2}}) \tag{9}$$

Equation (9) indicates that the noise level of an optimal combination is always smaller than that of L1 or L2. One example of such solutions is:

$$\begin{aligned} \mathbf{K}_1 &= (\mathbf{Q}_{\mathrm{L1}} + \mathbf{Q}_{\mathrm{L2}})^{-1}\mathbf{Q}_{\mathrm{L2}} \\ \mathbf{K}_2 &= (\mathbf{Q}_{\mathrm{L1}} + \mathbf{Q}_{\mathrm{L2}})^{-1}\mathbf{Q}_{\mathrm{L1}}. \end{aligned} \tag{10}$$

Proofs on this approach are given in Appendix A in Kim and Langley (2003). Another approach to mitigating

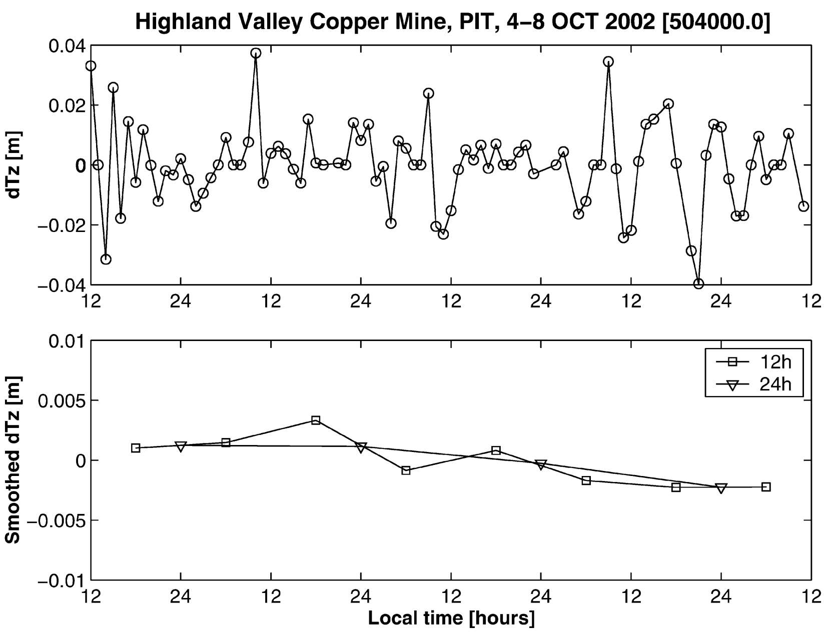

Fig. 5
Estimates of the residual tropospheric zenith delay at individual 1-h sessions over four consecutive days (*above*), and moving averages over 12 and 24 h (*below*)

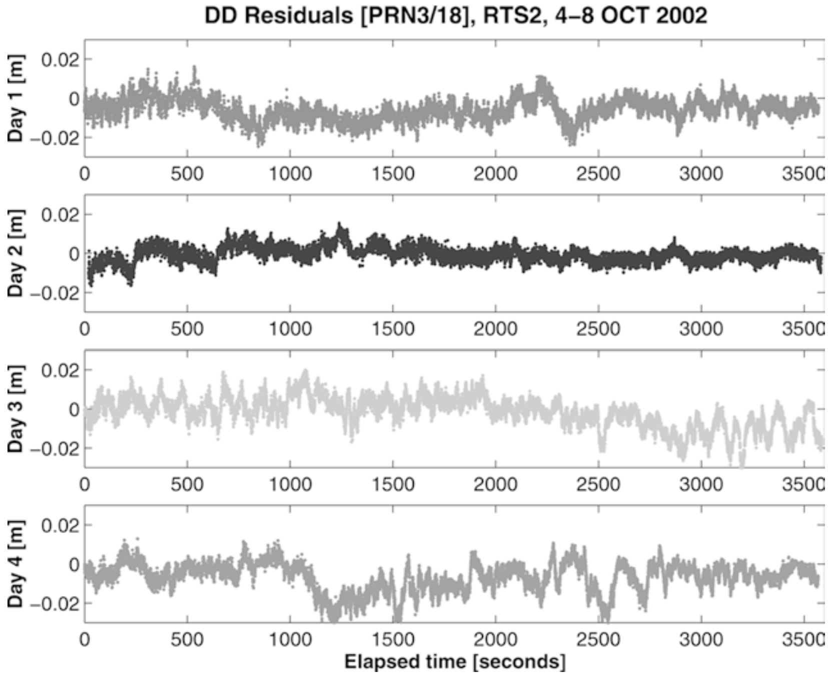

Fig. 6
Multipath observables (DD residuals) for the same 1-h session over four consecutive days

multipath is based on a smoothing process such as sequential least-squares estimation. Since the time constant of multipath is usually much shorter than an hour, for example, the parameter estimates sequentially estimated over 1-h session may be less contaminated by multipath.

Test results

The first campaign to investigate the performance of a hybrid monitoring system (combining RTSs with GPS) was carried out at Highland Valley Copper Mine in British Columbia over 1 week in early October 2002. Four geodetic performance dual-frequency GPS receivers and antennas (NovAtel OEM4 receivers and GPS-600 pinwheel antennas) were set up at the site. In order to monitor local deformation in this open-pit mine, a stable reference station (MAST) was set up outside the pit. Three monitoring stations (RTS1, RTS2 and PIT) were located inside the pit (Fig. 1). In this setting, the height differences between the reference station and each monitoring station was large, while slant distances between them were relatively short. This configuration is summarized in Table 1.

Since the monitoring stations are located in the pit, the visibility of GPS satellites at the stations is severely limited by the surrounding terrain. At PIT, for example, natural elevation cut-off angles due to the open pit environment range from 15 to 35 degrees (Fig. 2, above). Consequently, reduced satellite visibility leads to poor satellite geometry, which in turn causes degraded GPS positioning solutions. Large dilution of precision (DOP) values confirm this (Fig. 2, below), where x-axes in the first three panels are given in hour units in local time and the bottom panel shows that fewer than seven satellites are available over about 80% of the day.

Although the situations at RTS1 and RTS2 are slightly better than at PIT, as illustrated in Fig. 3, satellite geometry at these two stations is quite similar to that at PIT. As a result, all three stations provided very challenging situations in trying to attain sub-centimeter level, high-precision positioning solutions from the collected data.

Tropospheric delay

Like many other spatially dependent error sources, the effects of the tropospheric delay are usually negligible in relative positioning under short-baseline conditions. However, as illustrated in Fig. 4, the effects can be significant and cannot be cancelled by double-differencing if the height difference between two stations is large. To justify such a case in this application, the DD tropospheric delay observables were used:

$$\Delta\nabla\hat{T} = \Delta\nabla\Phi_1 - \Delta\nabla\rho - \lambda\Delta\nabla N_1 \qquad (11)$$

where $\nabla\Delta$ represents the DD operation. $\Delta\nabla\hat{T}$ is a compound error including the tropospheric delay, satellite orbit error, ionospheric delay, multipath, receiver system noise, etc. In the test set-up (i.e., short-baseline), we can expect that the DD tropospheric delay will be predominant in Eq. (11). Then, we compared the DD tropospheric delay "observable" (noisy curves in a dark color) with UNB3 prediction values (smooth curves in a light color) for the satellite pair of PRN 8 and 28 at RTS2 over the same 1-h session during four consecutive days. As depicted in Fig. 4, an order of 20 cm in the changes of the DD tropospheric delay occurs over 1 h, which confirms that the effects of tropospheric delay in the DD measurements are significant. Also, the figure shows that the UNB3 tropospheric delay model performs very well in this application. Unless the effects of tropospheric delay are removed from the carrier phase measurements, therefore, ambiguity resolution and cycle-slip correction can easily fail.

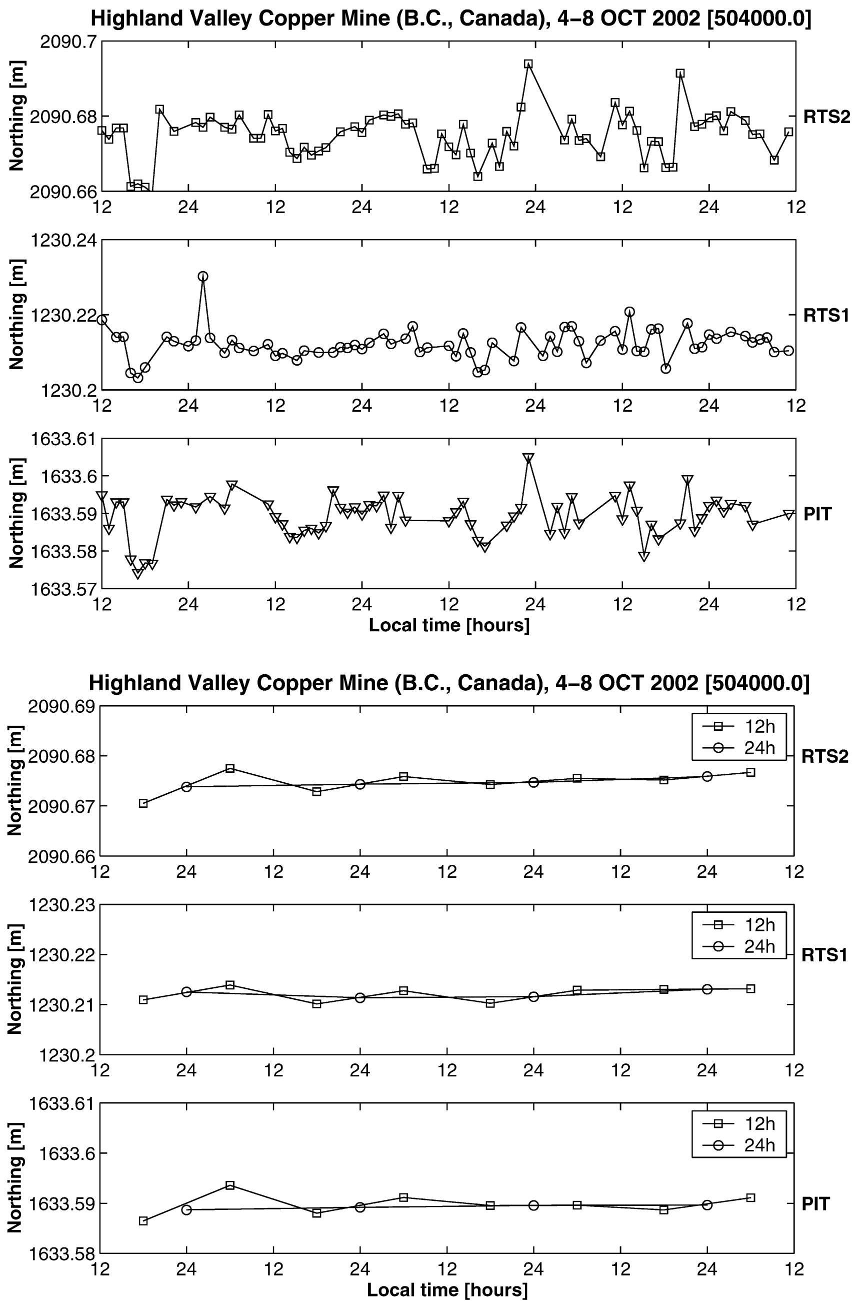

Fig. 7
Positioning solutions (northing) for individual 1-h session over four consecutive days (*above*), and moving averages over 12 and 24 h (*below*)

The residual tropospheric delay is the remaining part of the tropospheric delay not predicted by empirical models. To obtain the highest precision some advantage may be obtained by estimating the residual tropospheric zenith delay along with other unknown parameters such as the position coordinates. However, important limitations exist in the geometry of the satellite coverage. At high elevation angles, an error in the tropospheric zenith delay is almost indistinguishable from a bias in the height component, which means that an unmodeled tropospheric zenith delay error primarily causes an error in the height determination. It has been recommended to include data at low elevation angles (less than 10 degrees) for the tropospheric residual estimate to be meaningful (Collins and Langley 1997). Unfortunately, circumstances at the stations in the open-pit mine do not permit the acquisition of data at elevation angles less than 10 degrees. In fact, the lowest elevation angles visible from RTS1, RTS2 and PIT are 10, 10 and 15 degrees. As a result, the estimates of unmodeled tropospheric zenith delay error do not seem to be reliable (Fig. 5). The estimates are too noisy. A quick "back of the envelope" calculation suggests that these values should be less than 20 cm. Furthermore, we do not have any "truth" to justify the estimates. For this reason, unfortunately, we did not use these estimates in obtaining the positioning solutions.

Multipath

In general, multipath due to a single predominant reflector (usually, specular reflection from a smooth surface) shows an apparent daily correlation at a stationary GPS-receiving antenna. Since the same satellite

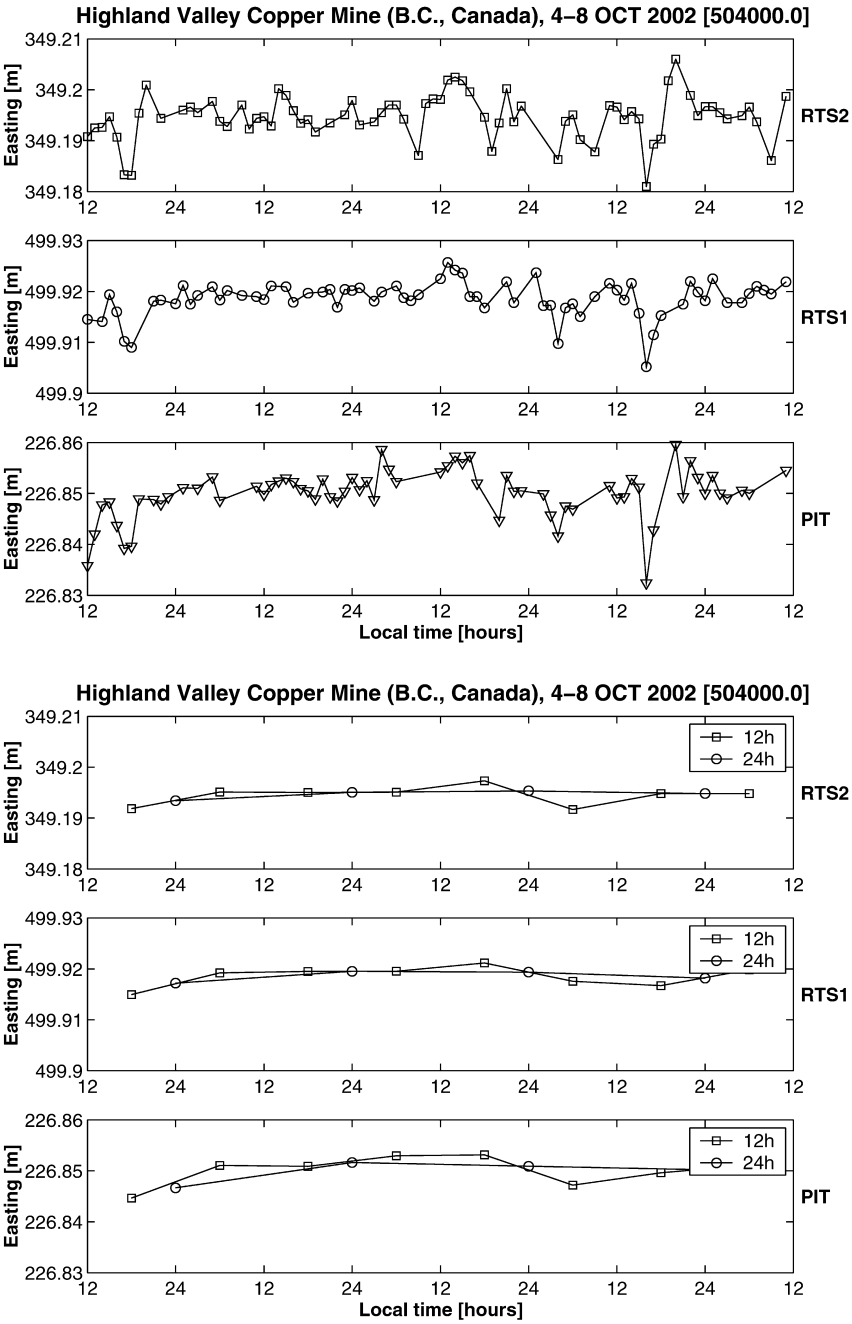

Fig. 8
Positioning solutions (easting) for individual 1-h session over four consecutive days (*above*) and moving averages of them over 12 and 24 h (*below*)

constellation geometry repeats each day, it is easy to see the same pattern repeated about 4 min earlier each day from the multipath observables as long as the receiving antenna remains stationary. However, multipath due to diffraction and diffusion may not show such an apparent daily correlation. Diffraction and diffusion (similar to multiple specular reflections) can easily change the scenario involving the reflecting objects. As a result, a GPS receiver may track the composite signal of a direct and (multiple) reflected(s) signal with different multipath characteristics every day. Figure 6 illustrates that the effects of multipath at the MAST and RTS2 stations are not correlated on a daily basis. The figure shows the DD residuals for satellite pair PRN 3/18 and stations MAST and RTS2. The residuals are dominated by multipath, receiver noise and any unmodeled effects. For this reason, we did not use the technique utilizing the repeatability of multipath at stationary stations (so-called stacking) to mitigate multipath in the measurements. Instead we used a smoothing process (i.e., sequential least-squares estimation over 1 h) and an optimal inter-frequency linear combination of L1 and L2 to reduce the effects of multipath.

Positioning solutions obtained using the modified UNB RTK software (albeit in a post-processing mode) are illustrated in Figs. 7, 8 and 9. First, we cut the data recorded over four consecutive days into 96 1-h sessions and processed each 1-h data set independently. Northing,

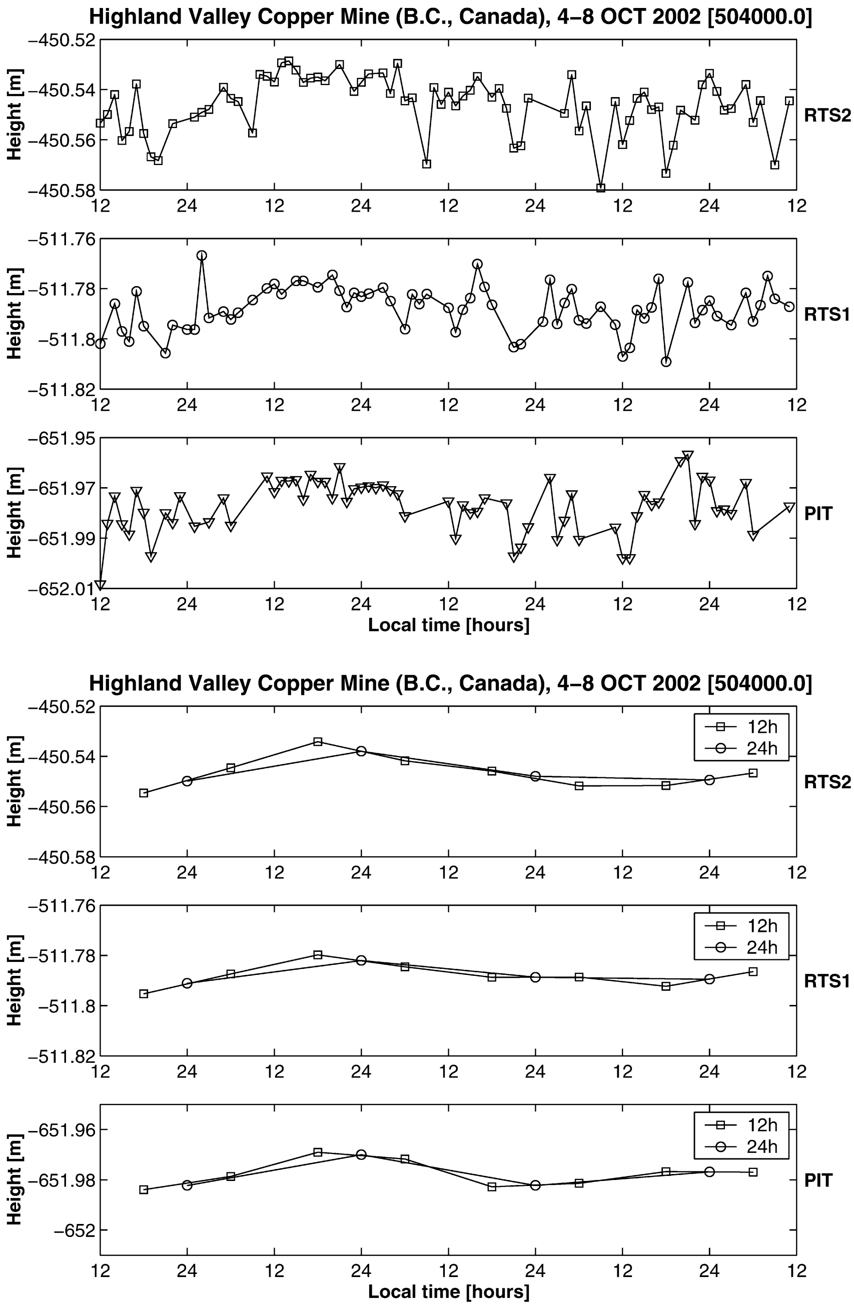

Fig. 9
Positioning solutions (height) for individual 1-h session over four consecutive days (*above*), and moving averages over 12 and 24 h (*below*)

Table 2
Mean values (in m) of 24-h moving average estimates of relative receiver positions (minimum/maximum deviation)

	Northing	Easting	Height
RTS1-MAST	1,230.212 (−0.0012/ 0.0009)	499.919 (−0.0018/ 0.0005)	−511.788 (−0.0039/ 0.0080)
RTS2-MAST	2,090.675 (−0.0006/ 0.0011)	349.195 (−0.0016/ 0.0003)	−450.546 (−0.0031/ 0.0060)
PIT-MAST	1,633.589 (−0.0003/ 0.0007)	226.850 (−0.0033/ 0.0016)	−651.978 (−0.0043/ 0.0079)

easting and height components of RTS1, RTS2 and PIT from MAST were estimated. Moving average values over 12 and 24 h were also computed. We outline the summary of positioning solutions in Tables 2 and 3. Table 2 shows the mean values of 24-h moving averages. We used these mean values as “truth” for Table 3.

Concluding remarks

The performance of the modified UNB RTK software shows promise, as indicated in Tables 2 and 3. Considering the requirement of a few millimeter accuracy at the 95% confidence level (particularly in height changes) for local deformation monitoring at an open-pit mine, there

Table 3
Summary of the positioning solutions with respect to 4-day mean for all 1-h sessions (all values are in m)

		Bias	Minimum	Maximum	1 σ	RMS
RTS1-MAST	ΔN	0.0001	−0.0088	0.0182	0.0041	0.0041
	ΔE	−0.0004	−0.0138	0.0067	0.0035	0.0035
	ΔH	0.0001	−0.0211	0.0212	0.0089	0.0089
RTS2-MAST	ΔN	−0.0003	−0.0155	0.0189	0.0062	0.0062
	ΔE	−0.0004	−0.0140	0.0110	0.0045	0.0045
	ΔH	−0.0002	−0.0332	0.0174	0.0112	0.0112
PIT-MAST	ΔN	0.0003	−0.0148	0.0160	0.0055	0.0055
	ΔE	−0.0001	−0.0176	0.0096	0.0049	0.0049
	ΔH	0.0005	−0.0303	0.0213	0.0103	0.0103

is still progress to be made to meet the requirement. The only exception is the 24-h moving average estimates. The minimum and maximum deviations from the mean values of the 24-h moving average estimates are within a few millimeters (Table 2).

We have faced two main issues during the first measurement campaign. First, we did not have "truth" to validate our approach. One typical example, which may lead us to draw misinterpretations and incorrect conclusions, is depicted in Fig. 7. The height solutions of the second day seem to be significantly different from those of the other 3 days. Furthermore, the height solutions of all three stations RTS1, RTS2 and PIT with respect to MAST seem to be commonly affected by some errors. Therefore we can conclude that something may have happened at MAST during the second day. Unfortunately, we have nothing to validate this conclusion from the first campaign. Second, the geometry of the satellite coverage in the open-pit prohibits us from obtaining the highest precision. Since we struggle with a few millimetres accuracy, we need to estimate the residual tropospheric zenith delay along with unknown parameters such as the position components. Unfortunately, circumstances at the stations do not permit us to obtain data at elevation angles less than 10 degrees. As a result, the estimates of unmodeled tropospheric zenith delay error seem not to be fully reliable.

In order to meet the requirements for this project, further research will be performed. At the present time, the use of pseudolites for deformation monitoring is being investigated. The use of pseudolites should address the issue of limited satellite availability, as indicated in a number of studies by other researchers (Barnes et al. 2002; Meng et al. 2002). A second measurement campaign is being planned to collect another set of data. Anomalies (data gaps in the observation files or a possible change in position of the MAST station) hinder sound analysis of the current data set. During this second campaign, meteorological data will be collected in an attempt to more accurately correlate tropospheric effects with solution variations. As well, RTSs will be used to monitor the stability of the GPS stations to serve as "truth".

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References

Barnes J, Wang J, Rizos C, Tsujii T (2002) The performance of a pseudolite-based positioning system for deformation monitoring. In: Proc 2nd Symp on Geodesy for Geotechnical and Structural Applications, Berlin, Germany, 21–24 May, pp 326–337

Braasch MS, Van Dierendonck AJ (1999) GPS receiver architectures and measurements. Proc IEEE 87(1):48–64

Collins JP, Langley RB (1997) Estimating the residual tropospheric delay for airborne differential GPS positioning. In: Proc 10th Int Technical Meeting of the Satellite Division of the Institute of Navigation, Kansas City, Missouri, 16–19 Sept, pp 1197–1206

Duffy M, Hill C, Whitaker C, Chrzanowski A, Lutes J, Bastin G (2001) An automated and integrated monitoring program for Dimond Valley Lake in California. In: Proc 10th Int Symp on Deformation Measurements (Metropolitan Water District of S. California), Orange, California, 19–22 March, CD ROM

Kim D, Langley RB (2001) Mitigation of GPS carrier phase multipath effects in real-time kinematic applications. In: Proc 15th Int Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, Utah, 11–14 Sept, pp 2144–2152

Kim D, Langley RB (2003) On ultrahigh-precision GPS positioning and navigation. Navigation J Inst Navigation 50(2):103–116

Kim D, Langley RB, Kim S (2002) Shipyard giants: high-precision crane guidance. GPS World 13(9):28–34

Kim D, Langley RB, Kim J, Kim S (2003) A gantry crane auto-steering system based on GPS RTK technology. In: Proc European Navigation Conf, GNSS 2003, Graz, Austria, 22–25 April

Meng X, Roberts GW, Dodson AH, Cosser E, Noakes C (2002) Simulation of the effects of introducing pseudolite data into bridge deflection monitoring data. In: Proc 2nd Symp on Geodesy for Geotechnical and Structural Engineering, Berlin, Germany, 21–24 May, pp 372–381

Niell AE (1996) Global mapping functions for the atmosphere delay at radio wavelengths. J Geophys Res 101(B2):3227–3246

Saastamoinen J (1973) Contributions to the theory of atmospheric refraction. In three parts. Bull Géodésique 105:279–298; 106:383–397; 107:13–34

Weill LR (2003) Multipath mitigation: how good can it get with new signals? GPS World 14(6):106–113

Wilkins R, Bastin G, Chrzanowski A, Newcomen W, Shwydiuk L (2003) A fully automated system for monitoring pit wall displacements. In: Proc SME Annu Conference, Cincinnati, Ohio, 24–26 Feb